DRAFT

# 12013

## Breccia with granite

82.3 grams

*Figure 1: Close-up photo of 12013,11. Field of view is 4.5 cm. NASA# S70-43636*

### Introduction

12013 is a unique lunar sample, but it did not appear to be remarkable to the astronauts when they picked it up (figure 1). It was not documented by surface photography, nor is its location or orientation known (although there is a large zap pit (~2 mm) on the end piece that was cut off (,8 W1). However, during preliminary examination, 12013 was found to have K = 2.02 wt. %, U = 10.7 ppm, Th = 34.3 ppm (LSPET 1970, O'Kelley et al. 1971) which was a good deal higher than that of other lunar samples.

According to Quick et al. (1981), lunar sample 12013 is best interpreted as a complex mixture of two polymict breccias (seen in figures 2 and 3). One is black and aphanitic and the other is mottled gray and white. There is sometimes a distinct boundary between these two general lithologies (figure 4). The black breccia is generally basaltic in composition, while the gray and white lithology is generally silica and potassium rich. Large vugs can be seen in the bulk rock (figure 1), and numerous small vesicles are seen in thin sections of the black lithology. Both lithologies are greatly enriched in trace elements.

The groundmass of the black breccia is a fine-grained intergrowth of plagioclase, pyroxene, ilmenite and phosphate minerals. The clast population is dominated by fragments of plagioclase, quartzofeldspathic rocks and norite. These clasts have not equilibrated with the groundmass. The chemical composition of the black breccia lithology is generally similar to KREEP.

The gray and white portion is generally granitic in composition, but includes as clasts, felsite, basalt and gabbro. The gray breccia lithology included felsite, quartzofeldspathic rock as large clasts that partially

*Figure 2: Photo of sawn surface of 12013,11showing "marbled" nature of light and dark breccia lithologies. Scale is in mm. NASA# S70-43171.*

melted and recrystallized. Granitic melt locally migrated to fill intersticies and is now a fine-grained intergrowth of K-feldspar and silica. Based on the very high K, U, Th in the bulk sample and light color (figure 1), the gray and white breccia lithology may be the dominant component of the remainder of 12013.

The source terrain for 12013 was unusual for the moon: consisting of various norites, basalts, gabbros, quartzofeldspathic and granitic rocks. However, material from mare basalt appears to be absent.

## Petrography

Albee et al. (1970), Drake et al. (1970) and Gay et al. (1970) initially studied a small portion of 12013 (figure 3). James (1970) studied 12013,6 which contains a large clast of felsite or granite (figure 4). McGee et al. (1979) and Quick et al. (1981a) provided further detailed description. Everyone concluded that 12013 is a complicated rock. *The good news (?) is that there remains more than 60 grams of pristine sample yet unstudied!*

**Mineralogical Mode 12013** (from Quick et al. 1981)

| | Black bx. mineral fragments | Gray bx. mineral fragments | felsite clasts | quartzo-feldspathic clasts |
|---|---|---|---|---|
| Plagioclase | 51.8 | 65 | 2 | 35 |
| K-feldspar | | 0.7 | 50 | 27 |
| Pyroxene | 17.2 | 15.6 | 5 | 3 |
| Olivine | 29.6 | 4.4 | | |
| Ilmenite | 1.4 | 2.7 | 1 | 10 |
| Silica | | 8.5 | 40 | 22 |
| Zircon | | 0.4 | tr. | tr. |
| Phosphate | | 1.3 | | |

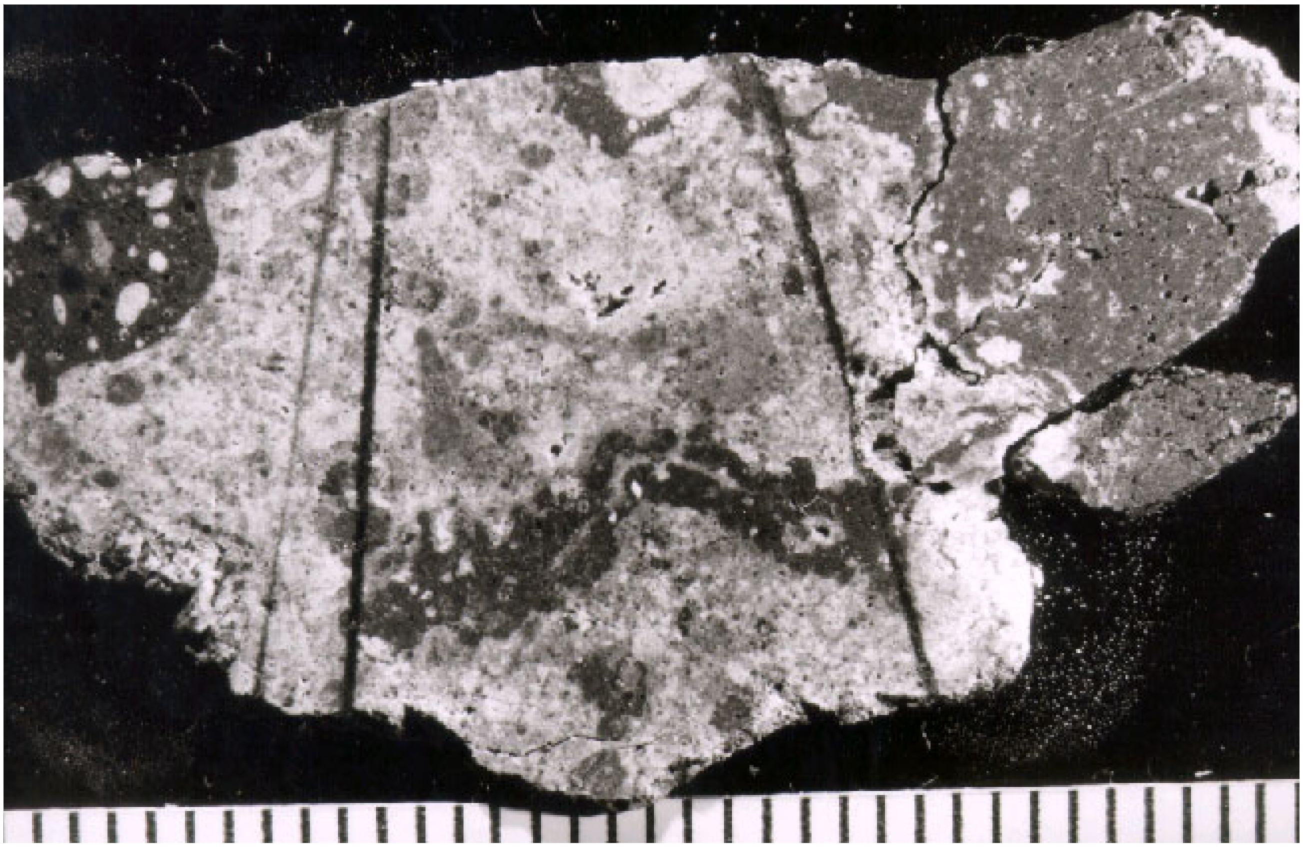

*Figure 3: Photo of 12013 slab ,9. Scale in mm. NASA# S70-40833 This thin slab was used to make thin sections ,13 ,14 ,15.*

Both the black and gray breccia lithologies exhibit reaction of clasts with the matrix and exhibit plastic flow indicating breccia formation at a high temperature. The mineral and lithic clast populations in these two lithologies are similar, but the percentages differ.

A felsite lithology within the gray lithology is characterized by intergrowths of quartz, K-feldspar, ilmenite and include long narrow (delicate) needles of high-Ca pyroxene that indicate crystallization from a melt (James 1970). This lithology lacks evidence of plastic flow since crystallization. Ovoids filled with felsite are also found in the back breccia lithology.

Numerous very small lithic clasts in both lithologies of 12013 were carefully studied and reported by Drake et al. (1970) and Quick et al. (1981a).

## Petrogenesis

The black breccia lithology is a fragment-laden melt rock probably formed by mixing cold, impact-produced, mineral and lithic fragments with superheated, impact-generated melt during a major impact (Simonds et al. 1976, Quick et al. 1981a). The clastic component of the gray lithology was fragmented and weakly shocked by impact. The apparent clast populations of both lithologies are approximately the same, although with different percentages. Only one impact is required; both lithologies may have formed simultaneously.

The question of whether silicate liquid immiscibility played a part in the origin of 12013 has been discussed by Rutherford and Hess (1978) and Quick et al. (1981a). There appears to be considerable confusion.

## Mineralogy

***Olivine***: The black breccia component has olivine $Fo_{46-82}$. The gray breccia component has olivine $Fo_{48-62}$.

***Pyroxene***: Pyroxene compositions are generally Fe-rich (figure 6). Some of the pyroxenes in the black breccia lithology are chemically zoned. Long delicate needles of Ca-rich pyroxene are found in the felsite portion. Various pyroxenes are found in lithic fragments.

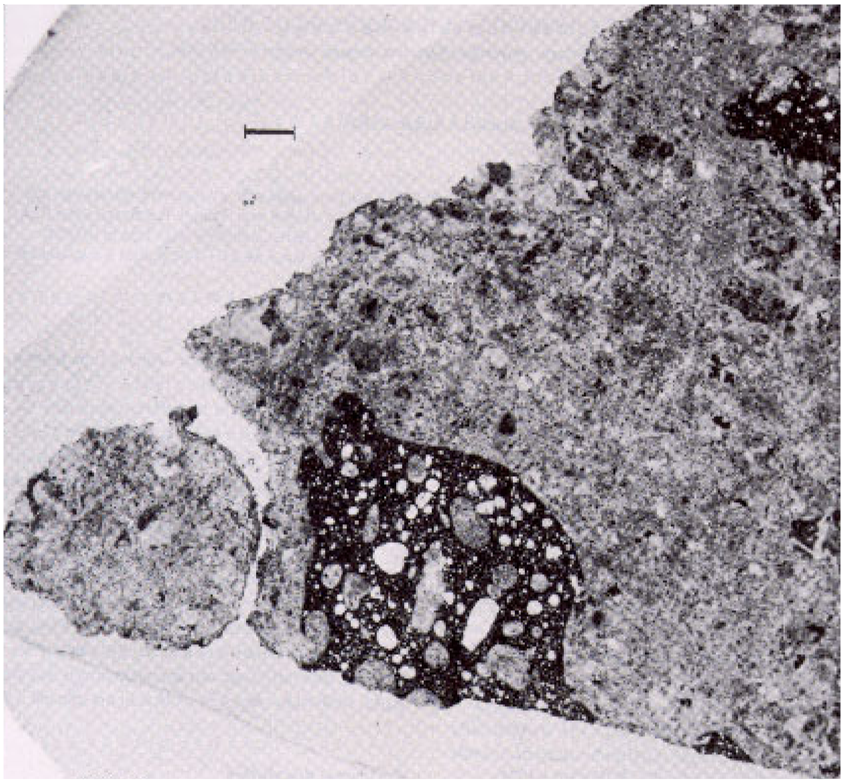

*Figure 4: Photomicrograph of thin section 12013,13 showing sharp boundary between light and dark lithologies. Scale bar is 1 mm.*

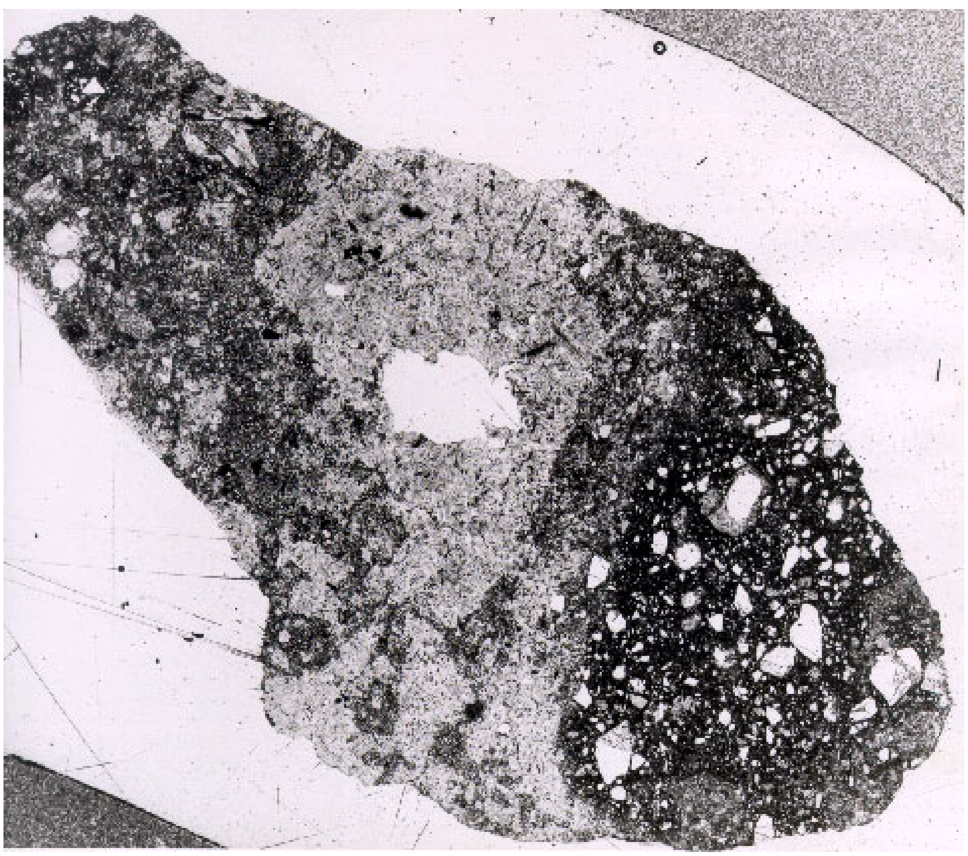

*Figure 5: Photomicrograph of thin section 12013,6 showing "felsite" clast. Field of view is 11 mm. NASA # S70-25410.*

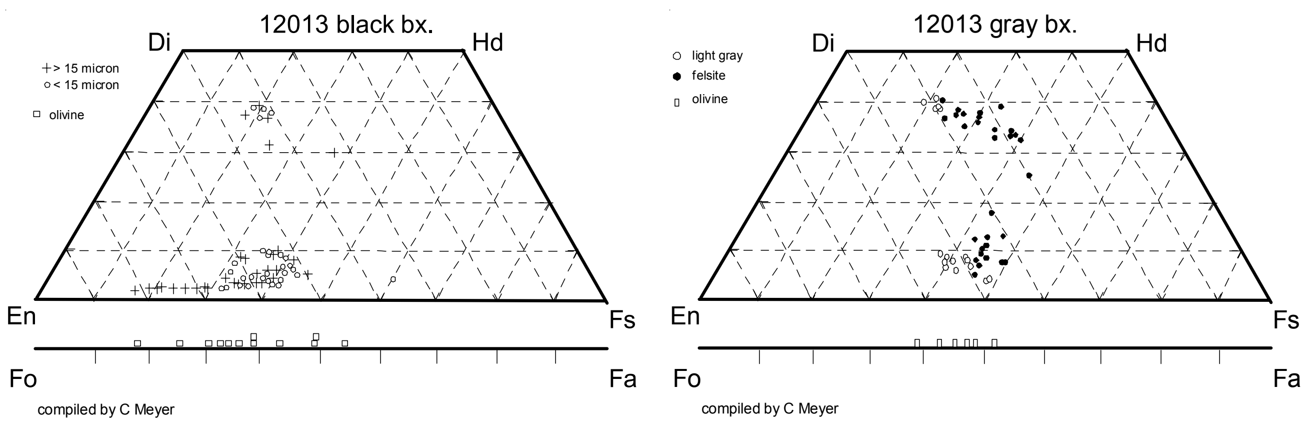


*Figure 6: Pyroxene compositions in dark and light lithologies of 12013. The data for the dark lithology are from Drake et al. (1970) figures 5 b and c, and light from figures 5 d and g (including felsite lithology). Pyroxenes from various lithic clasts generally omitted (see Drake et al. 1970, Albee et al. 1970, Quick et al. 1977). Olivine from Quick et al. (1981a).*

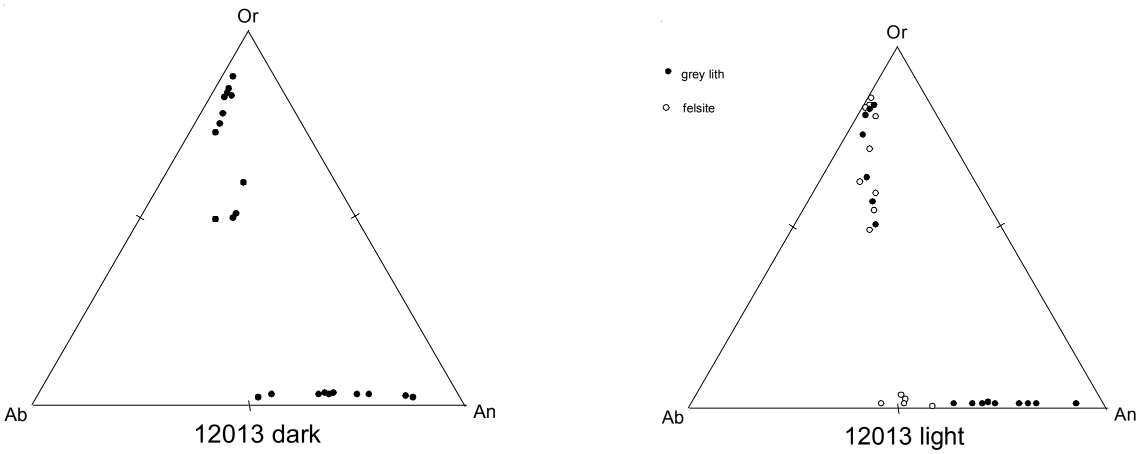


*Figure 7: Composition of feldspar clasts in light and dark breccia lithologies of 12013,6 replotted from James (1970).*

***Plagioclase***: Plagioclase found in lithic clasts and as mineral fragments in the matrix of both breccia lithologies range widely from >$An_{90}$ to $An_{50}$ (figure 7). Plagioclase in the felsite lithology is $An_{50}$.

***K-feldspar:*** Potassium feldspar is Ba-rich (1 – 2 wt. %). Some analyses indicate ternary feldspar (figure 7).

***Silica***: Drake et al. (1970) reported large crystal fragments (1 mm) of tridymite in the dark lithology. Most of the silica intergrown with K-spar in the felsite is now quartz, having reverted from tridymite (Quick 1981a).

***Ilmenite***: Some of the ilmenite in 12013 contains up to 1 % Nb (Quick et al. 1981a). Ilmenite with Nb = 1.9 % has been reported in the felsite.

***Accessory Minerals:*** Haines et al. (1971) studied U-bearing minerals including; whitlockite, apatite, zircon, phase beta and a Zr-Ti mineral rich in Fe, Nb, Y, REE. Gay et al. (1970) presented some crystallographic data for whitlockite and silica polymorphs.

***Zircon***: Albee et al. (1970) and Quick et al. (1981a) reported zircons in nearly every area they studied. Haines et al. (1971) and Compston et al. (1984) reported analyses of large zircons (>100 microns).

## Chemistry

LSPET (1970) and O'Kelley et al. (1971) determined that the bulk sample 12013 was extremely enriched in K, U and Th.

## Table 1a. Chemical composition of 12013,10.

| | 6 | 6 | 6 | 15 | 15 | 15 | 18 | 18 | 18 | 41 | 41 | 41 | 44 | 44 | 44 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *ref.* | Morgan70 | Wakita 70 | Laul 70 | Morgan | Wakita | Laul | Morgan | Wakita | Laul | Morgan | Wakita | Laul | Morgan | Wakita | Laul |
| *weight* | 88 mg | 86.5 mg | 85 mg | 99 | 98.3 | | 66 | 66.1 | | 32 | 31.7 | | 42 | 42.2 | |
| SiO2 % | 53.7 | | | 63.3 | | | 64 | | | 70.6 | | | 56.7 | | |
| TiO2 | | 3.17 | | | 0.83 | | | 0.83 | | | 0.83 | | | 0.67 | |
| Al2O3 | 13.4 | 14.7 | | 12.5 | 12.6 | | 11.9 | 11.9 | | 9.6 | 11.4 | | 11.9 | 13.2 | |
| FeO | 14.1 | 11.2 | | 11.5 | 9.1 | | 12.8 | 9.6 | | 14.1 | 9.6 | | 11.5 | 11.2 | |
| MnO | | 0.16 | | | 0.14 | | | 0.14 | | | 0.12 | | | | |
| MgO | | | | | | | | | | | | | | | |
| CaO | | 8.95 | | | 6.8 | | | 6.4 | | | 3.9 | | | 8.5 | |
| Na2O | | 1.36 | | | 1.27 | | | 1.36 | | | 1.26 | | | 1.21 | |
| K2O | | 0.58 | | | 2.2 | | | 2.1 | | | 3.6 | | | 0.73 | |
| P2O5 | | | | | | | | | | | | | | | |
| S % | | | | | | | | | | | | | | | |
| *sum* | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | |
| Sc ppm | | 25 | | | 24 | | | 22 | | | 20 | | | 30 | |
| V | | 50 | | | 70 | | | 100 | | | 70 | | | 90 | |
| Cr | | 1150 | | | 1130 | | | 1160 | | | 980 | | | 1660 | |
| Co | | 35 | 31 | | 18 | 16 | | 20 | 21 | | 28 | 34 | | 23 | 21 |
| Ni | | | | | | | | | | | | | | | |
| Cu | | | | | | | | | | | | | | | |
| Zn | | | 4.1 | | | 2.06 | | | 1.94 | | | 2.21 | | | 2.44 |
| Ga | | | 6.4 | | | 6.3 | | | 5.9 | | | 5.9 | | | 6 |
| Ge ppb | | | | | | | | | | | | | | | |
| As | | | | | | | | | | | | | | | |
| Se | | | | | | | | | | | | | | | |
| Rb | | | 13.5 | | | 66.5 | | | 49.4 | | | 98.7 | | | 20.7 |
| Sr | | | | | | | | | | | | | | | |
| Y | | | | | | | | | | | | | | | |
| Zr | | | | | | | | | | | | | | | |
| Nb | | | | | | | | | | | | | | | |
| Mo | | | | | | | | | | | | | | | |
| Ru | | | | | | | | | | | | | | | |
| Rh | | | | | | | | | | | | | | | |
| Pd ppb | | | | | | | | | | | | | | | |
| Ag ppb | | | 31.4 | | | 0.88 | | | 0.68 | | | 0.44 | | | 1.17 |
| Cd ppb | | | 34 | | | 91 | | | 44 | | | 300 | | | 24 |
| In ppb | | | 380 | | | 32 | | | 2.9 | | | 6.6 | | | 3.1 |
| Sn ppb | | | | | | | | | | | | | | | |
| Sb ppb | | | | | | | | | | | | | | | |
| Te ppb | | | | | | | | | | | | | | | |
| Cs ppm | | | 0.82 | | | 2.67 | | | 2.28 | | | 4.03 | | | 1.01 |
| Ba | | 1330 | | | 2790 | | | 2750 | | | 3900 | | | 1490 | |
| La | | 120 | | | 53 | | | 60 | | | 59 | | | 55 | |
| Ce | | | | | | | | | | | | | | | |
| Pr | | | | | | | | | | | | | | | |
| Nd | | | | | | | | | | | | | | | |
| Sm | | 51 | | | 18.8 | | | 21.9 | | | 19.3 | | | 21.8 | |
| Eu | | 3.4 | | | 1.9 | | | 0.9 | | | 1.8 | | | 2.4 | |
| Gd | | | | | | | | | | | | | | | |
| Tb | | | | | | | | | | | | | | | |
| Dy | | | | | | | | | | | | | | | |
| Ho | | | | | | | | | | | | | | | |
| Er | | | | | | | | | | | | | | | |
| Tm | | | | | | | | | | | | | | | |
| Yb | | 39 | | | 30 | | | 30 | | | 37 | | | 24 | |
| Lu | | 5.1 | | | 4 | | | 4.1 | | | 5.5 | | | 3.2 | |
| Hf | | 36 | | | 19 | | | 21 | | | 24 | | | 20 | |
| Ta | | | | | | | | | | | | | | | |
| W ppb | | | | | | | | | | | | | | | |
| Re ppb | | | | | | | | | | | | | | | |
| Os ppb | | | | | | | | | | | | | | | |
| Ir ppb | | | 4.6 | | | 0.05 | | | 0.72 | | | 10 | | | 0.84 |
| Pt ppb | | | | | | | | | | | | | | | |
| Au ppb | | | 3.1 | | | 0.21 | | | 0.46 | | | 0.45 | | | 0.34 |
| Th ppm | | 19 | | | 25 | | | 26 | | | 37 | | | 14 | |
| U ppm | | 6 | | | 9.2 | | | 8.8 | | | 12.4 | | | 6.1 | |

*technique (a) RNAA, INAA*

## Table 1b. Chemical composition of 12013,10.

| | 37+24 | 37+24 | 37+24 | 35 | 35 | 35 | AVE | | LSPET | | 18 | gray | white | black | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *ref.* | Morgan70 | Wakita 70 | Laul 70 | Morgan | Wakita | Laul | Anders 71 | | Anderson 70 | | Hubbard 70 | | | | |
| *weight* | | 49.4 mg | | | 56.7 | | | | | | 28.75 | 25.33 | 13.14 | 41.45 | |
| SiO2 % | 60.76 | | | 53.27 | | | | (a) | 61 | (b) | | | | | |
| TiO2 | | 1.33 | | | 1.5 | | | (a) | 1.2 | (b) | | | | | |
| Al2O3 | 13.04 | 11.3 | | 12.3 | 12.6 | | | (a) | 11.9 | (b) | | | | | |
| FeO | 16.7 | 12.1 | | 20.6 | 13 | | | (a) | 10 | (b) | | | | | |
| MnO | | 0.16 | | | 0.2 | | | (a) | 0.12 | (b) | | | | | |
| MgO | | | | | | | | | 6 | (b) | 4.6 | 8.3 | 0.85 | 9.1 | (c ) |
| CaO | | | | | | | | | 6.3 | (b) | 3.85 | 7.65 | 4.26 | 10.6 | (c ) |
| Na2O | | | | | | | | | 0.69 | (b) | 0.75 | 1.08 | 1.93 | 1.29 | (c ) |
| K2O | | | | | | | | | 2 | (b) | 1.17 | 0.68 | 5.08 | 1.16 | (d) |
| P2O5 | | | | | | | | | | | | | | | |
| S % | | | | | | | | | | | | | | | |
| *sum* | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | |
| Sc ppm | | 28 | | | 38 | | | (a) | 21 | (b) | | | | | |
| V | | 80 | | | 100 | | | (a) | 13 | (b) | | | | | |
| Cr | | 1770 | | | 2300 | | | (a) | 1050 | (b) | | | | | |
| Co | | 35 | 34 | | 25 | 27 | 26 | (a) | 13 | (b) | | | | | |
| Ni | | | | | | | | | 105 | (b) | | | | | |
| Cu | | | | | | | | | | | | | | | |
| Zn | | | 2.85 | | | 3.04 | 2.77 | (a) | | | | | | | |
| Ga | | | 6 | | | 6 | 6.1 | (a) | | | | | | | |
| Ge ppb | | | | | | | | | | | | | | | |
| As | | | | | | | | | | | | | | | |
| Se | | | 68 | | | 75 | 94 | (a) | | | | | | | |
| Rb | | | 50 | | | 26.7 | 42 | (a) | 33 | (b) | 29.4 | 20.9 | 128.7 | 9.8 | (d) |
| Sr | | | | | | | | | 150 | (b) | 105.5 | 147.8 | 235 | 214.9 | (d) |
| Y | | | | | | | | | 240 | (b) | | | | | |
| Zr | | | | | | | | | 2200 | (b) | | | | | |
| Nb | | | | | | | | | 170 | (b) | | | | | |
| Mo | | | | | | | | | | | | | | | |
| Ru | | | | | | | | | | | | | | | |
| Rh | | | | | | | | | | | | | | | |
| Pd ppb | | | | | | | | | | | | | | | |
| Ag ppb | | | 3.49 | | | 3.8 | 1.65 | (a) | | | | | | | |
| Cd ppb | | | 64 | | | 40 | 71 | (a) | | | | | | | |
| In ppb | | | 2.8 | | | 3.9 | 3.7 | (a) | | | | | | | |
| Sn ppb | | | | | | | | | | | | | | | |
| Sb ppb | | | | | | | | | | | | | | | |
| Te ppb | | | | | | | | | | | | | | | |
| Cs ppm | | | 2.37 | | | 1.26 | 1.9 | (a) | | | | | | | |
| Ba | | 2720 | | | 1810 | | | (a) | 2150 | (b) | 1662 | 1850 | 7278 | 1162 | (d) |
| La | | 50 | | | 37 | | | (a) | | | 45.4 | 37.5 | 81.4 | 98 | (d) |
| Ce | | | | | | | | | | | 116 | 91.8 | 199 | 267 | (d) |
| Pr | | | | | | | | | | | | | | | |
| Nd | | | | | | | | | | | 62.8 | 47.4 | 97.2 | 156 | (d) |
| Sm | | 17.9 | | | 14 | | | (a) | | | 18 | 13.9 | 27.8 | 44.7 | (d) |
| Eu | | 1.7 | | | 1.4 | | | (a) | | | 1.6 | 2.19 | 3.96 | 3.38 | (d) |
| Gd | | | | | | | | | | | 22.4 | | 32.6 | | (d) |
| Tb | | | | | | | | | | | | | | | |
| Dy | | | | | | | | | | | 26.3 | 22.2 | 46 | 55.8 | (d) |
| Ho | | | | | | | | | | | | | | | |
| Er | | | | | | | | | | | 18.2 | 16.3 | 34 | 35.1 | (d) |
| Tm | | | | | | | | | | | | | | | |
| Yb | | 29 | | | 19 | | | (a) | 20 | (b) | 20.8 | 19.9 | 40.6 | 34.4 | (d) |
| Lu | | 4 | | | 2.7 | | | (a) | | | 2.91 | 2.8 | 5.8 | 4.66 | (d) |
| Hf | | 18 | | | 20 | | | (a) | | | | | | | |
| Ta | | | | | | | | | | | | | | | |
| W ppb | | | | | | | | | | | | | | | |
| Re ppb | | | | | | | | | | | | | | | |
| Os ppb | | | | | | | | | | | | | | | |
| Ir ppb | | | 0.5 | | | 0.19 | 0.434 | (a) | | | | | | | |
| Pt ppb | | | | | | | | | | | | | | | |
| Au ppb | | | 2.37 | | | 13.2 | 0.353 | (a) | | | | | | | |
| Th ppm | | 25 | | | 12 | | | (a) | | | | | | | |
| U ppm | | 9.7 | | | 4.6 | | | (a) | | | | | | | |

*technique (a) RNAA, INAA, (b) PET OES, (c ) AA, (d) IDMS*

## Table 1c. Chemical composition of 12013,10.

| | felsite | KREEP | | 10 | 15 | 8 | 23 | 37 + 24 | 8 | 15 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *reference* | Janssens 78 | | | | Charlie Schnetzler 1970 | | | | | | | LSPET 70 | |
| *weight* | 5.85 | 5.99 | | 10 | 5.2 | 37 | 68 | 33.4 | 18.4 | 14.5 | | | |
| SiO2 % | | | | | | | | | | | | 61 | (c ) |
| TiO2 | | | | | | | | | | | | 1.2 | (c ) |
| Al2O3 | | | | | | | | | | | | 12 | (c ) |
| FeO | | | | | | | | | | | | 10 | (c ) |
| MnO | | | | | | | | | | | | 0.12 | (c ) |
| MgO | | | | | | | | | | | | 6 | (c ) |
| CaO | | | | | | | | | | | | 6.3 | (c ) |
| Na2O | | | | | | | | | | | | 0.69 | (c ) |
| K2O | | | | 0.94 | 0.69 | 0.53 | 1.77 | 2.06 | 2 | 4.59 | (b) | 2 | (c ) |
| P2O5 | | | | | | | | | | | | | |
| S % | | | | | | | | | | | | | |
| *sum* | | | | | | | | | | | | | |
| | | | | | | | | | | | | | |
| Sc ppm | | | | | | | | | | | | 21 | (c ) |
| V | | | | | | | | | | | | 13 | (c ) |
| Cr | | | | | | | | | | | | 1050 | (c ) |
| Co | | | | | | | | | | | | 13 | (c ) |
| Ni | <50 | 260 | (a) | | | | | | | | | 105 | (c ) |
| Cu | | | | | | | | | | | | | |
| Zn | 2.5 | 3.9 | (a) | | | | | | | | | | |
| Ga | | | | | | | | | | | | | |
| Ge ppb | 30.5 | 409 | (a) | | | | | | | | | | |
| As | | | | | | | | | | | | | |
| Se | 0.4 | 0.93 | (a) | | | | | | | | | | |
| Rb | 55.5 | 4.94 | (a) | 25.8 | 18.7 | 14.3 | 47.4 | 56.7 | 57.2 | 127 | (b) | 33 | (c ) |
| Sr | | | | 200 | 157 | | 120 | 131 | | 126 | (b) | 150 | (c ) |
| Y | | | | | | | | | | | | 240 | (c ) |
| Zr | | | | | | | | | | | | 2200 | (c ) |
| Nb | | | | | | | | | | | | 170 | (c ) |
| Mo | | | | | | | | | | | | | |
| Ru | | | | | | | | | | | | | |
| Rh | | | | | | | | | | | | | |
| Pd ppb | <4 | 13 | (a) | | | | | | | | | | |
| Ag ppb | 1.76 | 1.2 | (a) | | | | | | | | | | |
| Cd ppb | 48 | 37 | (a) | | | | | | | | | | |
| In ppb | 28 | 3.6 | (a) | | | | | | | | | | |
| Sn ppb | | | | | | | | | | | | | |
| Sb ppb | 0.25 | 1.14 | (a) | | | | | | | | | | |
| Te ppb | <13 | 15 | (a) | | | | | | | | | | |
| Cs ppm | 2.7 | 0.71 | (a) | | | | | | | | | | |
| Ba | | | | 1610 | 895 | 956 | 2560 | 2770 | 3450 | 5790 | (b) | | |
| La | | | | | | | | | | | | | |
| Ce | | | | 341 | 374 | 283 | 92.7 | 115 | 169 | 136 | (b) | | |
| Pr | | | | | | | | | | | | | |
| Nd | | | | 205 | 224 | 176 | 48 | 56.8 | 92.7 | 62.5 | (b) | | |
| Sm | | | | 56.2 | 61.9 | 46.6 | 13.8 | 16.5 | 26.4 | 18 | (b) | | |
| Eu | | | | 3.52 | 2.76 | 3.21 | 2.24 | 2.22 | 2.81 | 2.1 | (b) | | |
| Gd | | | | 65.7 | 73.2 | 58.7 | 16.8 | 20.4 | 32 | 21.7 | (b) | | |
| Tb | | | | | | | | | | | | | |
| Dy | | | | 72.7 | 80.6 | 63.1 | 25.3 | 29.4 | 43 | 33.6 | (b) | | |
| Ho | | | | | | | | | | | | | |
| Er | | | | 43.9 | 48.1 | 37.5 | 18.5 | 22.6 | 29 | 27.4 | (b) | | |
| Tm | | | | | | | | | | | | | |
| Yb | | | | 41 | 47.1 | 36.2 | 23 | 27.4 | 32 | 34.4 | (b) | 20 | (c ) |
| Lu | | | | 6.36 | 6.95 | 5.4 | 3.67 | 4.3 | 5.18 | 5.64 | (b) | | |
| Hf | | | | | | | | | | | | | |
| Ta | | | | | | | | | | | | | |
| W ppb | | | | | | | | | | | | | |
| Re ppb | 0.028 | 0.26 | (a) | | | | | | | | | | |
| Os ppb | 0.09 | 5.84 | (a) | | | | | | | | | | |
| Ir ppb | 0.17 | 7.64 | (a) | | | | | | | | | | |
| Pt ppb | | | | | | | | | | | | | |
| Au ppb | 0.081 | 3.97 | (a) | | | | | | | | | | |
| Th ppm | | | | | | | | | | | | | |
| U ppm | 11.15 | 5.71 | (a) | | | | | | | | | | |

*technique (a) RNAA, (b) IDMS, (c ) optical emission spec.*

## Table 2. Chemical composition of 12013.

| | black bx. | black | black | gray | gray | gray | | black bx. | felsite | felsite | | **KREEP** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *reference* | Quick 77 | | | | | | | Quick 77 | | | | Warren 1988 |
| *weight* | 1.52 mg | 2.04 mg | 6.16 mg | 1.21 mg | 0.98 mg | 5.25 mg | | | | | | |
| SiO2 % | | | | | | | | 50.1 | 73.1 | 73 | (b) | 50.3 |
| TiO2 | 1.9 | 4.6 | 3.3 | 0.75 | 0.86 | 0.3 | (a) | 2.2 | | 0.6 | (b) | 2 |
| Al2O3 | 12.5 | 11.9 | 14.6 | 11.1 | 9.8 | 10.1 | (a) | 13.2 | 12.1 | 11.9 | (b) | 15.1 |
| FeO | 14.2 | 13.3 | 13.7 | 9.6 | 6 | 14 | (a) | 12.3 | 1.3 | 1.4 | (b) | 10.3 |
| MnO | 0.158 | 0.164 | 0.166 | 0.122 | 0.077 | 0.15 | (a) | 0.15 | | | (b) | |
| MgO | 10.7 | 8.6 | 9 | 6.3 | 5.5 | 8.5 | (a) | 7.4 | 0.5 | 0.7 | (b) | 8.3 |
| CaO | 7.3 | 8.9 | 9.7 | 4.1 | 3.8 | 4.6 | (a) | 9.5 | 1.5 | 1.4 | (b) | 13.9 |
| Na2O | 1.45 | 1.47 | 1.45 | 1.28 | 1.17 | 1.12 | (a) | 1.9 | 1.4 | 1.4 | (b) | 0.94 |
| K2O | 0.37 | 0.5 | 0.4 | 3.74 | 3.03 | 2.6 | (a) | 0.06 | 6.7 | 6.8 | (b) | 0.96 |
| P2O5 | | | | | | | | 1.2 | 0.2 | 0.13 | (b) | 0.8 |
| S % | | | | | | | | | | | | |
| *sum* | | | | | | | | | | | | |
| | | | | | | | | | | | | |
| Sc ppm | 23 | 30 | 28 | 21 | 17 | 25 | (a) | | | | | 23 |
| V | 33 | 46 | 34 | 47 | 42 | 61 | (a) | | | | | 40 |
| Cr | 889 | 985 | 1108 | 1034 | 493 | 472 | (a) | | | | | 1200 |
| Co | 29 | 24 | 27 | 12 | 8.6 | 24 | (a) | | | | | 25 |
| Ni | | | | | | | | | | | | |
| Cu | | | | | | | | | | | | 20 |
| Zn | | | | | | | | | | | | 5 |
| Ga | | | | | | | | | | | | 9 |
| Ge ppb | | | | | | | | | | | | 500 |
| As | | | | | | | | | | | | |
| Se | | | | | | | | | | | | |
| Rb | 16 | 33 | 10 | 124 | 101 | 87 | (a) | | | | | 22 |
| Sr | | | | | | | | | | | | 200 |
| Y | | | | | | | | | | | | 400 |
| Zr | 940 | 1140 | 2070 | 1130 | 720 | 690 | (a) | | | | | 1400 |
| Nb | | | | | | | | | | | | 100 |
| Mo | | | | | | | | | | | | |
| Ru | | | | | | | | | | | | |
| Rh | | | | | | | | | | | | |
| Pd ppb | | | | | | | | | | | | |
| Ag ppb | | | | | | | | | | | | |
| Cd ppb | | | | | | | | | | | | |
| In ppb | | | | | | | | | | | | |
| Sn ppb | | | | | | | | | | | | |
| Sb ppb | | | | | | | | | | | | |
| Te ppb | | | | | | | | | | | | |
| Cs ppm | 1.8 | 2.1 | 1.7 | 4 | 4.3 | 3.1 | (a) | | | | | 1 |
| Ba | 660 | 1430 | 390 | 4150 | 4160 | 3760 | (a) | | | | | 1300 |
| La | 135 | 130 | 135.7 | 64 | 39 | 56.5 | (a) | | | | | 110 |
| Ce | 333 | 344 | 347 | 170 | 100 | 151 | (a) | | | | | 280 |
| Pr | | | | | | | | | | | | 37 |
| Nd | 242 | 219 | 215 | 91 | 59 | 74 | (a) | | | | | 178 |
| Sm | 53 | 53 | 59 | 20 | 13 | 19 | (a) | | | | | 48 |
| Eu | 2.52 | 3.29 | 3.89 | 1.85 | 1.74 | 2.14 | (a) | | | | | 3.3 |
| Gd | | | | | | | | | | | | 58 |
| Tb | 10.6 | 11.4 | 12.5 | 4.9 | 3.7 | 5.2 | (a) | | | | | 10 |
| Dy | 67 | 70 | 75 | 38 | 23 | 33 | (a) | | | | | 65 |
| Ho | | | | | | | | | | | | 14 |
| Er | | | | | | | | | | | | 40 |
| Tm | | | | | | | | | | | | 5.7 |
| Yb | 36 | 37 | 39 | 35 | 25 | 30 | (a) | | | | | 36 |
| Lu | 4.8 | 4.5 | 5.2 | 5.2 | 3 | 4.2 | (a) | | | | | 5 |
| Hf | 32 | 38 | 63 | 23 | 25 | 27 | (a) | | | | | 38 |
| Ta | 3.9 | 9.1 | 5.3 | 6.6 | 5 | 7.1 | (a) | | | | | 5 |
| W ppb | | | | | | | | | | | | 3 |
| Re ppb | | | | | | | | | | | | |
| Os ppb | | | | | | | | | | | | |
| Ir ppb | | | | | | | | | | | | |
| Pt ppb | | | | | | | | | | | | |
| Au ppb | | | | | | | | | | | | |
| Th ppm | 17.2 | 17 | 24.5 | 44.8 | 35.6 | 47 | (a) | | | | | 22 |
| U ppm | 5.3 | 6.2 | 10.4 | 12.1 | 10.4 | 14.2 | (a) | | | | | 6.1 |

*technique (a) INAA, (b) DBA elec. Probe*

**Table 3: Additional composition data for 12013**

| | sample # | U ppm | Th ppm | K ppm | Rb ppm | Sr ppm | weight |
|---|---|---|---|---|---|---|---|
| O'Kelley et al. 1971 | | 10.3 | 34.2 | 20400 | | | 80 g |
| | | 9.8 | 32.2 | 21100 | | | 66 g |
| Hubbard et al. 1970 | ,18 | | | 9750 | 29.4 | 105.5 | 28 mg |
| | gray | | | 5670 | 20.9 | 147.8 | 25 mg |
| | white | | | 42200 | 128.7 | 235 | 13 mg |
| | black | | | 3830 | 9.8 | 215 | |
| Bottino et al. 1971 | 10 dark | | | | 25.8 | 200 | |
| Schnetzler et al. 1970 | 10 dark | | | | 18.7 | 157 | |
| | 8 felds | | | | 38.4 | 329 | |
| | 23 lih, dark | | | | 47.4 | 120 | |
| | 37 + 24 | | | | 56.7 | 131 | |
| | 8 light | | | | 57.2 | 161 | |
| | 15 light | | | | 127 | 126 | |
| | 15 A< 2.62 | | | | 197 | 151 | |
| | 15 B | | | | 112 | 159 | |
| | 15 D | | | | 15.4 | 50.3 | |
| Rosholt and Tatsumoto 1971 | 10,9 | 5.67 | 20.73 | | | | |
| Tatsumoto 1970 | 10,42 | 10.8 | 34.29 | | | | |
| | 10,45 | 5.75 | 19.05 | | | | |
| Albee et al. 1970 | A | | | | 46.1 | 120 | |
| | B | | | | 49.7 | 88 | |
| | 40 | | | | 49.6 | 114 | |
| | 29 | | | | 32.5 | 157 | |
| | 45 | | | | 76.9 | 102 | |
| | 42 | | | | 104.6 | 107 | |
| | Comp A | | | | 81.7 | 264 | |
| | 35 | | | | 24.4 | 198 | |
| | 9 | | | | 8 | 317 | |

Morgan and Ehmann (1970), Wakita and Schmitt (1970) and Laul et al. (1970) analyzed the same seven (7) splits of 12013 (table 1). Hubbard et al. (1970), Schnetzler et al. (1970), Ma et al. (1977) and Quick et al. (1977) also analyzed numerous splits (figure 8). The dark portions have the chemical composition of KREEP (figure 9), while the light portions have granitic composition (with high K, Ba and Rb) that is distinguished by a bowed-down REE pattern (red in figure 8).

The granitic portion seems to be relatively low in meteoritic siderophiles (Ir, Au, Re) (Laul et al. 1970, Anders et al. 1971, Janssens et al. 1978).

Although the petrography study of the thin slabs (,9 ,10) described 12013 as being made of two lithologies (black and gray), the high K, U, Th of the bulk sample (O'Kelley) indicates that the gray lithology is the main component.

## Radiogenic age dating

The age of breccia formation of 12013 seems to be about 4 b.y., but the high initial $^{87}Sr/^{86}Sr$ ratio and very radiogenic Pb indicate that the granitic component of the rock was formed earlier (Nyquist 1977, Wasserburg et al. 1977). Quick et al. (1981b) provide a summary and reinterpretation of the age dating attempted on 12013. They conclude that the granitic component is at least as old as 4.17 b.y and could possibly be as old as 4.5 b.y.

Turner (1970, 1971) dated 12013 by $^{39}Ar/^{40}Ar$ plateau at 4.03 b.y (figure 10). Albee et al. (1970) and Wasserburg et al. (1977) dated the rock by Rb/Sr at 3.99 b.y. (figure 11) and Bottino et al. (1971) at 4.08 (figure 12). Haines et al. (1971) determined the age of various U-Th-rich minerals by electron probe analysis (average $4 \pm 0.1$ b.y.). Hinthorne and Andersen (1974) used the ion microprobe to directly date U-rich zirconolite in the granitic component. Andersen and Hinthorne (1972) and Meyer et al. (1990) determined old ages for zircons (see table).

Albee et al. (1970) and Tatsumoto (1970, 1971) reported U-Th-Pb data for numerous splits, but the discussion is beyond comprehension. It is clear that Pb has been partially redistributed during breccia formation making age dating impossible by this technique.

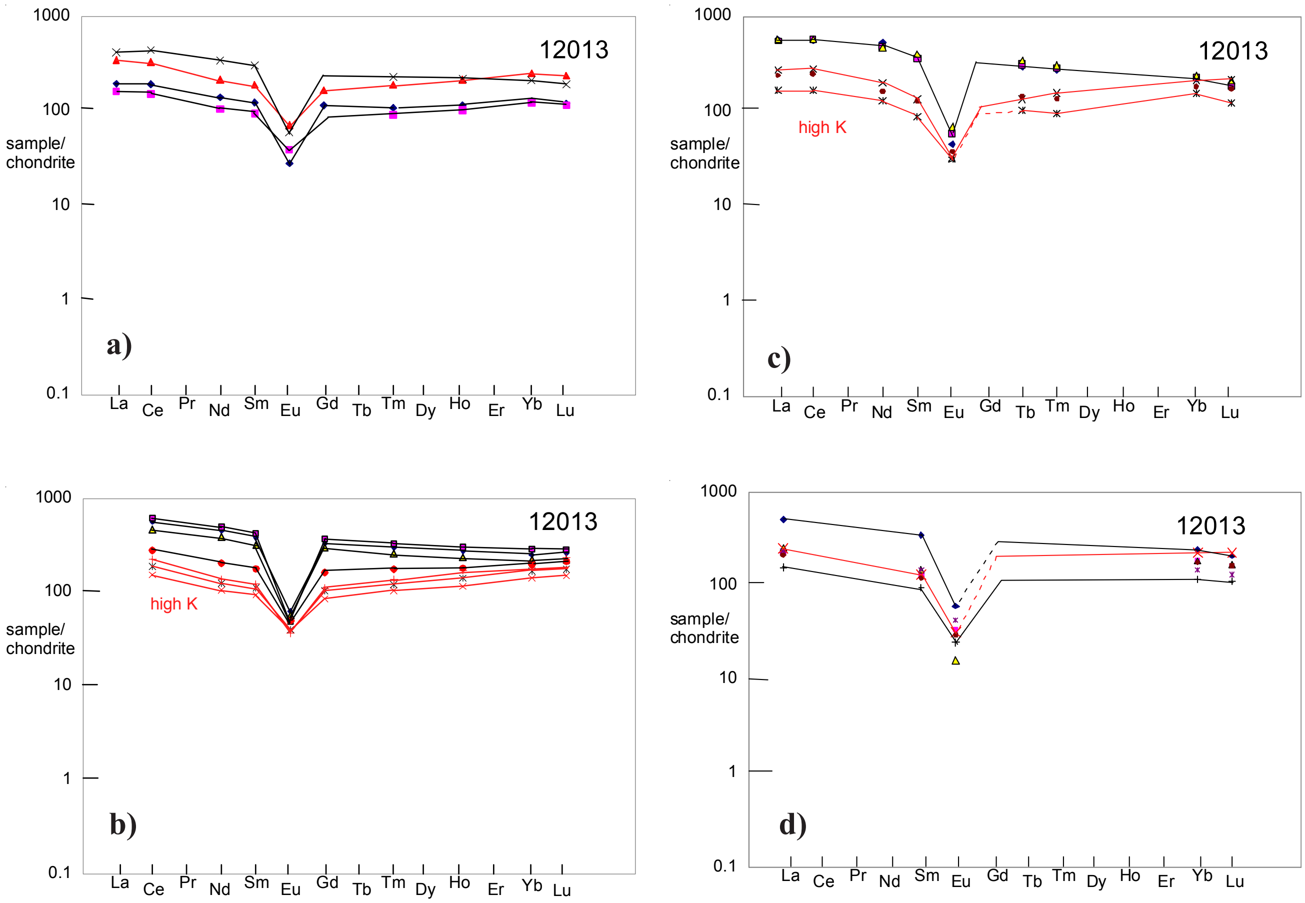


*Figure 8: Normalized rare-earth-element patterns for 12013. a) from Hubbard et al 1970, b) from Schnetzler et al. 1970, c) from Quick et al. 1977, d) from Wakita et al. 1970. Red is for samples with high K, Rb, Ba.*

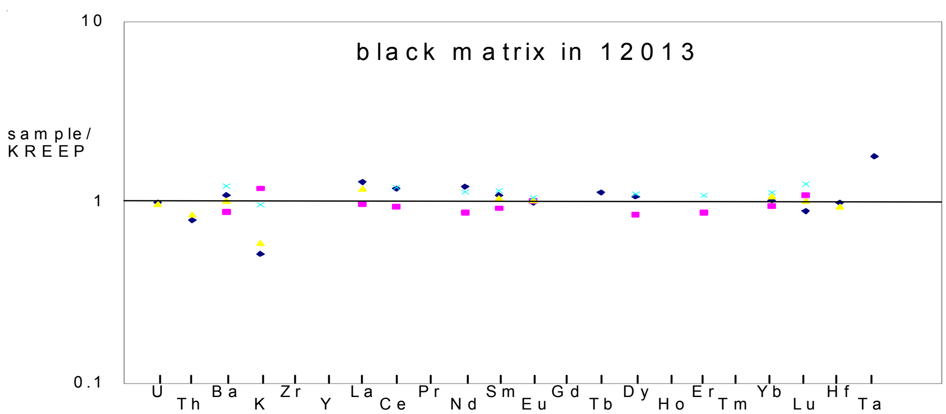


*Figure 9: Chemical composition of black lithology of 12013 normalized by KREEP composition as estimated by Warren and Wasson 1980. Data selected from tables 1 and 2.*

Alexander (1970), Schaeffer et al. (1970), Turner (1971) and Kaiser (1971) discuss the significant outgassing of $^{40}Ar$ and $^{4}He$.

## Cosmogenic isotopes and exposure ages

Alexander (1970) determined the cosmic ray exposure age as 60 ± 12 m.y. using $^{3}He$ and $^{21}Ne$. Kaiser (1971) also determined exposure ages for 12013 by various techniques.

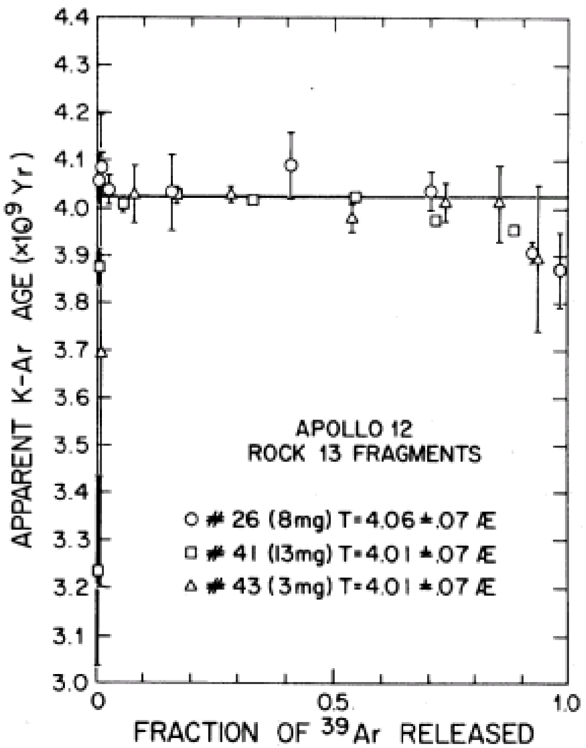


*Figure 10: Ar release diagram for 12013 from Turner (1971).*

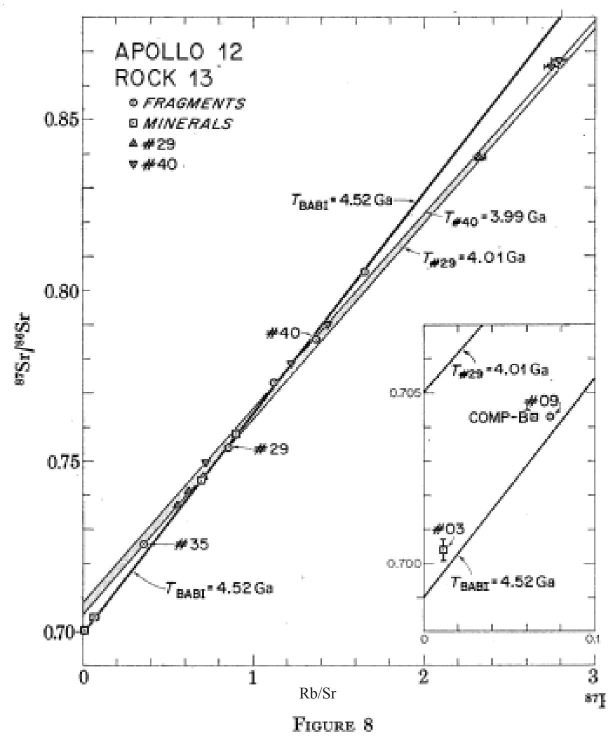


*Figure 11: Rb/Sr isochron diagram for 12013 from Albee et al. (1970) and Wasserburg et al. (1977).*

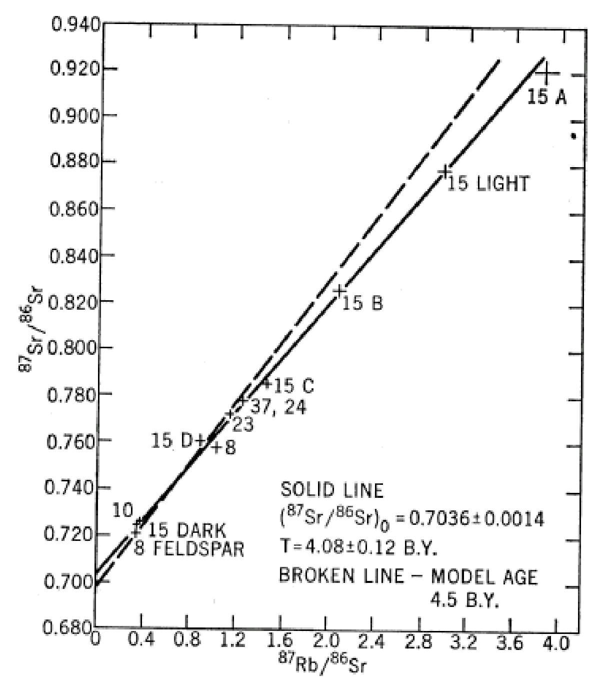


*Figure 12: Rb/Sr isochron or mixing diagram for 12013 as determined by Bottino et al. 1971.*

## Other Studies

Burnett et al. (1970 and 1971) studied fossil tracks in 12013. Taylor and Epstein (1970) determined the isotopic composition of silicon and oxygen. Rare gas studies were reported by LSPET (1970), Albee et al. (1970), Alexander (1970), Schaeffer et al. (1970) and Kaiser (1971). There was no evidence for Xe from $^{244}$Pu nor $^{129}$I. Rosholt and Tatsumoto (1971) studied U and Th isotopic systems.

## Processing

12013 was subdivided and carefully studied by a consortium at the California Institute of Technology (Anderson 1970). At first, a chip of 12013 was used to make 3 thin sections (,6 see flow diagram). Then a wire saw (with minimum kurf) was used to saw off one end and make two thin slabs (figure 13-16). One slab (figure 3) was used to make three additional thin sections (,14 ,15). The adjacent slab (,10) was subdivided in a clean lab and distributed to numerous investigators. Another chip (,6) was used for Pb isotope studies. The remainder of the rock remains unstudied since the early 1970s!

## Summary of Age Data for 12013

| | Ar/Ar | Rb/Sr | Pb/Pb | U-Th-Pb |
|---|---|---|---|---|
| Turner 1971 | 4.03 ± 0.07 | | | |
| Albee et al. 1970 | | 3.99 ± 0.05 | | |
| | | 4.01 ± 0.09 | | |
| Bottino et al. 1971 | | 4.08 ± 0.12 | | |
| Quick et al. 1981b | | *~ 4.0 reinterpretation* | | |
| Tatsumoto 1970 | | | *3.91 ± 0.1 assuming various assumptions* | |
| Tatsumoto 1971 | | | 4.37 | |
| Haines et al. 1971 | | | | *4.00 ± 0.1 electron probe* |
| Andersen and Hinthorne 1972 | | | *4.25 zircon* | |
| Hinthorne and Andersen 1974 | | | *3.89 zirconolite* | |
| *Meyer et al. 1990* | | | *4.2-4.3 zircon (unpublished)* | |

***Caution: Decay constants have not been corrected.***

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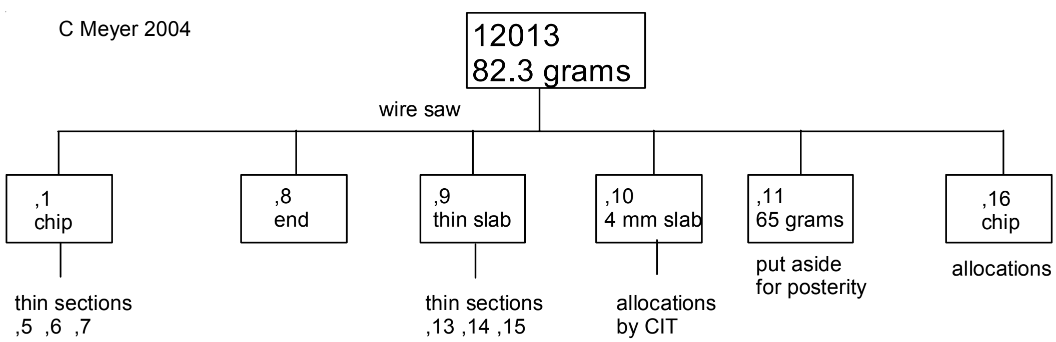

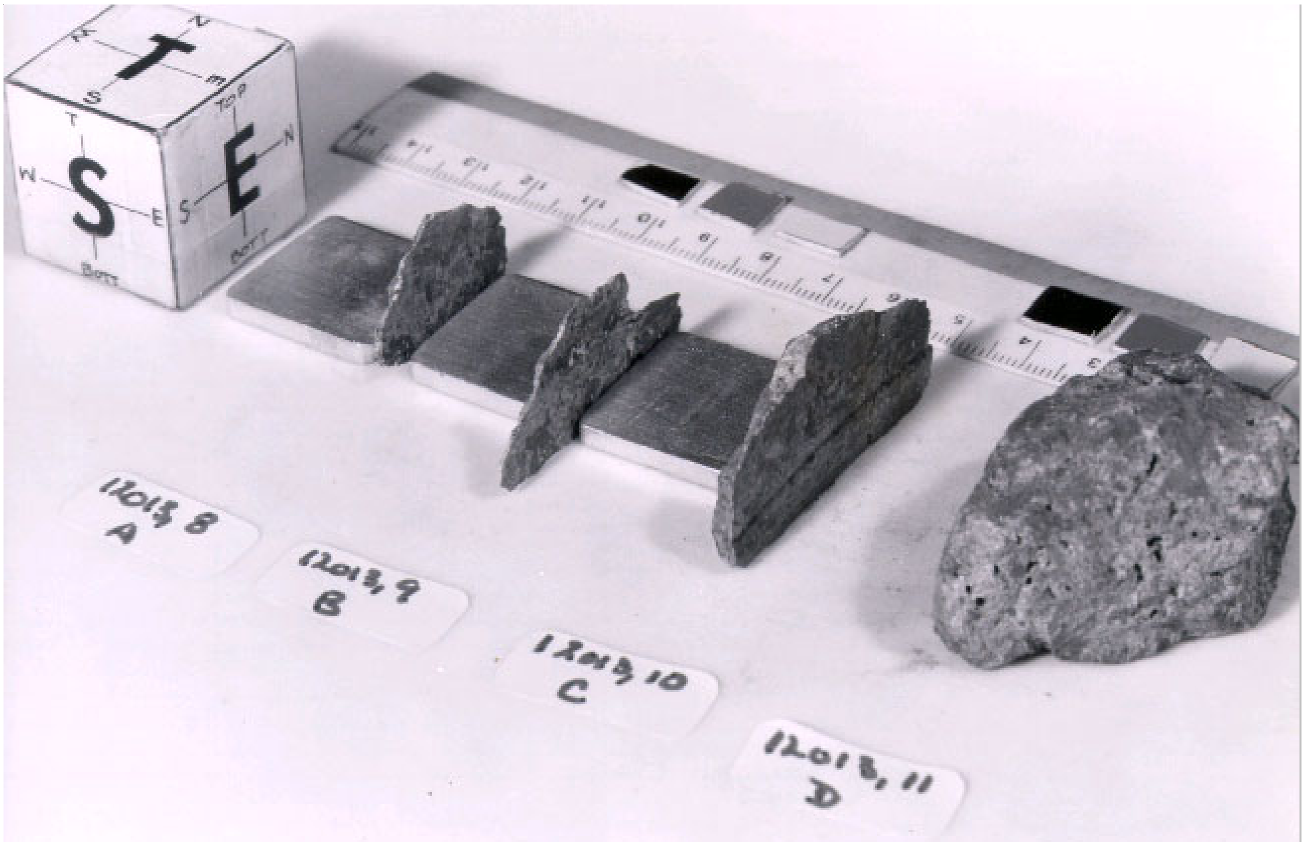


*Figure 13: Parts diagram after cutting 12013 in 1970.*

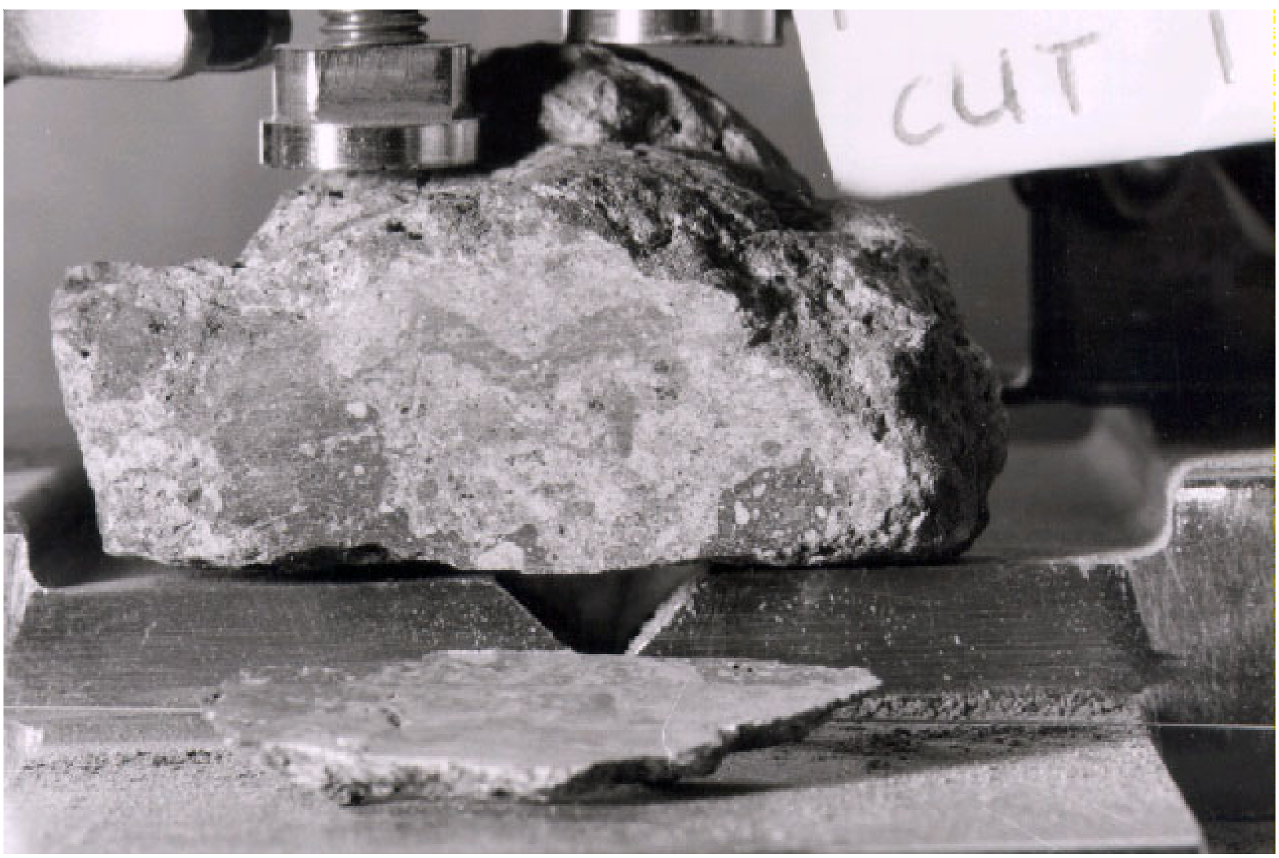


*Figure 14: Photo after 1st saw cut of 12013. End piece ,8 is laying in the foreground. NASA# S70-40679*

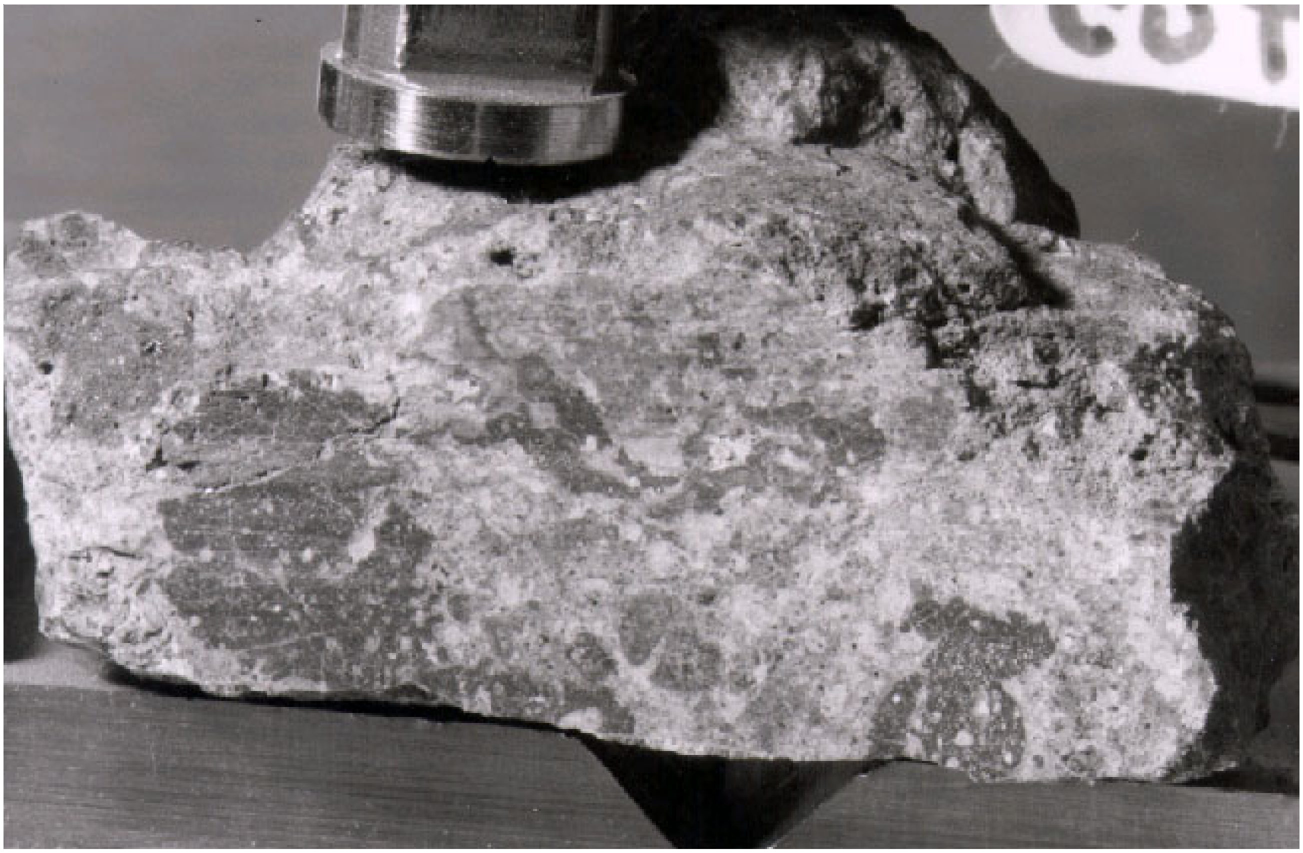

*Figure 15:   Photo after 2nd saw cut of 12013.  NASA S70-40673*

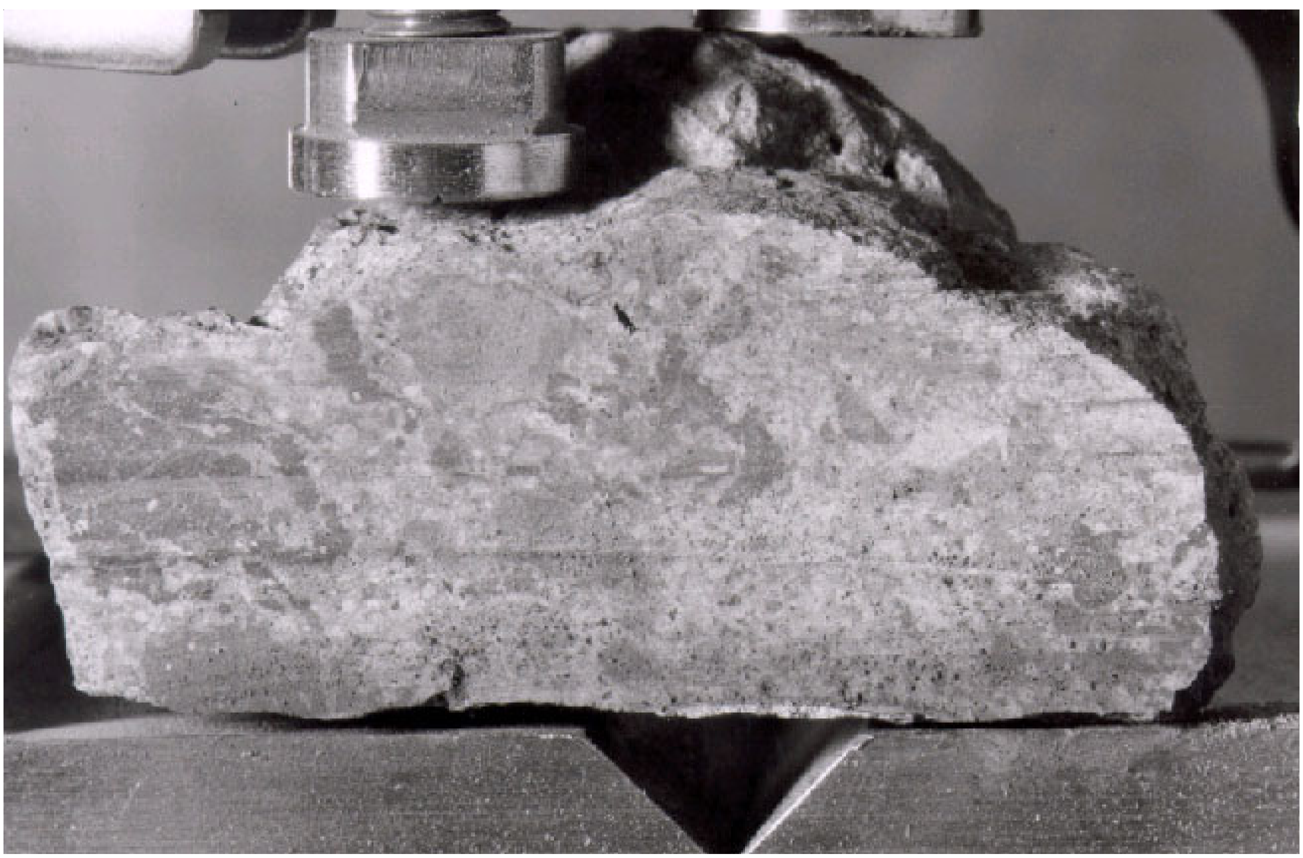

*Figure  16:   Photo after 3rd saw cut of 12013.  NASA#S70-40682.  Compare with figure 2.*